BBC

ENGINEERING DIVISION

MONOGRAPH

NUMBER 56: DECEMBER 1964

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by

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BRITISH BROADCASTING CORPORATION

PRICE FIVE SHILLINGS

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IN THE PHASE/FREQUENCY AND AMPLITUDE/FREQUENCY
CHARACTERISTICS

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PREVIOUS ISSUES IN THIS SERIES

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SUMMARY

In a stereophonic broadcasting system, differences between the phase/frequency or amplitude/frequency characteristics of the left and right channels may result in unwanted displacement or dispersion of the sound images across the stage; interchannel phase differences, moreover, may impair the volume or quality of the compatible monophonic transmission.

These effects have been subjectively assessed and the resulting data used to derive limits for the permissible interchannel difference in phase/frequency and amplitude/frequency characteristics.

The experiments were carried out as a contribution to the work of the European Broadcasting Union (EBU).

1. Introduction to Parts I and II

The position of the virtual sound image produced by applying a pair of correlated signals to two spaced loudspeakers depends on the relative amplitudes and phases of the two signals. Unintentional differences in amplitude or phase between these signals can thus lead to displacement of the reproduced image from its intended position, and where this displacement varies with frequency, the various components of a complex sound may be dispersed across the stage, producing a blurred image. It is therefore important, in planning a distribution system for stereophonic programmes, to assess quantitatively the subjective effect of disparities between the amplitude/frequency and phase/frequency characteristics of the left- and right-hand channels and to discover what degree of difference can be allowed without introducing appreciable changes in the stereophonic presentation. In the case of broadcasting, it may be necessary to consider in addition the effect of such differences between channels on the transmission of the corresponding compatible monophonic programme. To obtain the necessary information, the subjective tests to be described were carried out in the BBC Research Department; the work formed part of a series of experiments, undertaken as a contribution to an international study of stereophony organized by the European Broadcasting Union (EBU). Other experiments in this series have been described in earlier monographs.[1,2]

The investigation was divided into two parts, the first, covered in Part I of this monograph, dealing with differences in phase/frequency characteristics between the left- and right-hand channels, and the second, covered in Part II, with differences in amplitude/frequency characteristics.

PART I

THE EFFECT OF INTERCHANNEL DIFFERENCES IN THE PHASE/FREQUENCY CHARACTERISTICS

2. General

For the sake of brevity, the term 'interchannel phase (or time) difference' will be used to denote unwanted differences arising from lack of similarity between the channels, as distinct from any intentional difference in phase (or time) between the original left- and right-hand signals.

At frequencies for which the wavelength of the sound is greater than the dimensions of the human head, the image position is a function of the phase difference between signals in the left- and right-hand channels. At higher frequencies, however, it is the envelopes of the left- and right-hand signals which are significant in directional hearing,[3] so that the relevant quantity is not the difference in phase between corresponding components but the difference in time of arrival of the signals as a whole. Any disparity between the phase characteristics of the two channels has therefore to be considered partly in terms of phase differences and partly in terms of differences in group delay time.

Little information has so far been published* on the influence, on a stereophonic image, of interchannel—as distinct from interaural—phase differences, except where these take the form of a straightforward interchannel time delay. Early tests made in the BBC using pairs of lines having known differences in group delay time, supplemented by experiments in which known interchannel delays were introduced by magnetic recording devices, indicated that the minimum perceptible time difference was of the order of 250 μs.[4] Other investigators came to similar conclusions,[5] and in 1960 a figure of 200 μs was provisionally adopted by the EBU Working Party S (Stereophony) as the maximum allowable difference in group delay time between the left- and right-hand channels.

The above criterion is, however, open to two objections. In the first place, it fails to meet the requirement of multiplex transmission systems in which the sum of the left- and right-hand signals is used to provide a compatible monophonic programme. In such systems, differences in time delay between the two channels, if large enough, produce interference effects within the audio-frequency band which adversely affect the frequency characteristic for monophonic reception; thus, if the left- and right-

* Reference 7 describes experiments carried out by IRT concurrently with the work described in Part I of this monograph.

hand signals are equal in amplitude, an interchannel time difference of 200 μs would produce a complete cancellation of the resultant monophonic signal at 2·5 kc/s, 7·5 kc/s, and 12·5 kc/s. To guard against such effects, the EBU Working Party S in 1961 tentatively proposed an over-riding requirement that the difference in phase shift between the left- and right-hand channels should be limited to 90°, a figure which can readily be shown to give a maximum loss of 3 dB in the sum signal; the subjective effect of this loss depends, however, on the frequency at which it occurs and such a criterion could not therefore be accepted without further investigation. In the second place, the practice of specifying interchannel phase differences only in terms of time delay imposes unnecessarily stringent requirements at the lower end of the audio-frequency range; for example, a time difference of 200 μs corresponds at 50 c/s to a phase difference of only 3·6°, a figure which is known from experience to be negligible. To meet both these objections and also to obtain data on which practical tolerances for a broadcast distribution system could be based, it was therefore decided to carry out the subjective experiments to be described, which cover the lower and upper regions of the audio-frequency band and take into account the quality of the monophonic programme as well as the impairment of stereophony.

For the purpose of these experiments, interchannel phase differences were divided into two categories:

(a) Phase differences existing between channels for which the bandwidths and the amplitude/frequency responses within the pass band are substantially identical.

(b) Phase differences associated with differences in amplitude/frequency response between the channels within the pass band.

The experiments described in Part I of this Monograph were confined to condition (a); reference to condition (b) is made in Part II.

For case (a), it has been shown theoretically, and verified by measurements carried out in the BBC, that within the pass band of an equalized transmission channel, such as an S.B.* line, the variations of phase shift with frequency may be represented, with a sufficient accuracy for the present purpose, by

$$\theta = K_1 f - K_2 / f$$

where θ is the phase shift at frequency f and K_1, K_2 are constants for the channel. The phase difference between any two such channels can clearly be expressed in the same form, and the present experiments were designed to reproduce approximately this condition. The upper and lower ends of the frequency range were separately investigated, the interchannel phase differences being made proportional to frequency in the former case and inversely proportional in the latter; this procedure leads to a slightly higher interchannel phase difference in the midband region than would occur in practice.

The team of observers consisted of thirteen engineering

* A long-established BBC abbreviation for 'Simultaneous Broadcasting'. The more generally used expression is 'Programme Distribution'.

staff from the BBC Research Department Electro-Acoustics Group, all experienced in quality assessment. The arrangements for sound reproduction were similar to those described in an earlier monograph,[2] to which reference may be made for details not given here. In observing the stereophonic effects, the observer was seated equidistant from a pair of well-matched wide-range loudspeakers concealed behind acoustically transparent curtains; a series of vertical black tapes, spaced apart by a tenth of the effective stage width, formed a scale against which image displacements could be assessed. Most of the tests were carried out under simulated domestic conditions in a listening-room having a volume of 85 m³ and a reverberation time of 0·34 sec at 500 c/s, but some of them were repeated in an acoustically dead sound-measurement room having a wall reflexion coefficient of less than 10 per cent for frequencies above 80 c/s. In assessing the effect of interchannel phase differences on the quality of the compatible programme, the signals from the two channels were combined and fed to a single loudspeaker in the listening-room; the observer was seated at a distance of 1·5 m in front of the loudspeaker.

Existing data[3] indicate that the rate of change of image position with interchannel time difference is greatest when this time difference is small and when the interchannel amplitude difference is also small. The effect of interchannel phase differences on the stereophonic presentation may therefore be expected to be most noticeable when the original left- and right-hand signals are equal and in phase, i.e. when the stereophonic image is intended to appear to a central observer to be in the centre of the stage. The same condition is also the most critical for the quality of the compatible monophonic programme, since the variation in the sum of two signals which results from a variation in the phase angle between them is greatest when the two amplitudes are equal. To simulate this state of affairs, signals from a common source were applied to the two channels, the required interchannel phase shift being effected by all-pass networks introduced into one or the other. All tests were repeated with the left- and right-hand channels interchanged.

3. Interchannel Phase Difference Increasing at High Frequencies

3.1 *Effect of Interchannel Phase Difference on Quality of Compatible Monophonic Signal*

3.1.1 *Experimental Details*

In these tests, the phase shift circuit consisted of a series of delay networks giving phase shift proportional to frequency. Fig. 1, curve (a), shows the resulting frequency characteristic of the sum signal derived from a pair of identical left- and right-hand signals when the interchannel time difference was 25 μs, corresponding to an interchannel phase difference of 90° at 10 kc/s; for greater or lesser values of time difference the curve is displaced up or down the frequency scale. The amount of delay introduced into the circuit was varied in steps of 5 μs by a rotary switch under the control of the observer; additional
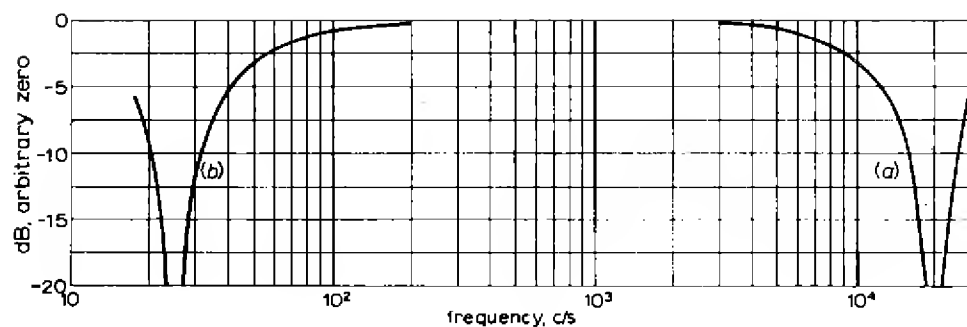
Fig. 1 — *Frequency characteristics of compatible signal produced by the summation of identical left- and right-hand signals after transmission over separate channels*

Curve (a) For interchannel phase difference proportional to frequency, reaching 90° at 10 kc/s (interchannel time difference 25 μs)
Curve (b) For interchannel phase difference inversely proportional to frequency, reaching 90° at 50 c/s

delay, the amount of which was unknown to the observer, was introduced by the experimenter and varied from test to test, so that there was no fixed relationship between the setting of the rotary switch and the constants of the system. For each test the observer was asked to find the switch position beyond which a change of quality of the programme became apparent, i.e. the point at which rotation of the control knob in one direction produced an audible change in quality while an equal rotation in the opposite direction had no effect. The degree of quality impairment corresponding to this setting of the control will for the sake of brevity be referred to hereafter as 'imperceptible'.

The programme material consisted of recorded excerpts of Latin-American music—chosen because of its extended high-frequency range—solo violin, and female speech. The test passages varied in duration from seven seconds to

Interchannel Time Difference Imperceptible on Compatible Monophonic Programme

TABLE 1 — 50 *per cent of Tests*

Item	Upper frequency limit 13 kc/s			Upper frequency limit 10 kc/s			Upper frequency limit 6·8 kc/s		
	Interchannel time difference	Interchannel phase difference at 13 kc/s	Loss in compatible signal at 13 kc/s	Interchannel time difference	Interchannel phase difference at 10 kc/s	Loss in compatible signal at 10 kc/s	Interchannel time difference	Interchannel phase difference at 6·8 kc/s	Loss in compatible signal at 6·8 kc/s
Latin-American music	22·8 μs	107°	−4·5 dB	29·7 μs	107°	−4·5 dB	36·3 μs	89°	−2·9 dB
Female speech	27·6 μs	129°	−7·3 dB	32·5 μs	117°	−5·6 dB	44·1 μs	108°	−4·6 dB
Violin	32·6 μs	152°	−12·3 dB	37·0 μs	133°	−8·0 dB	45·5 μs	111°	−4·9 dB

TABLE 2 — 90 *per cent of Tests*

Latin-American music	15·7 μs	74°	−1·9 dB	20·0 μs	72°	−1·8 dB	26·6 μs	65°	−1·5 dB
Female speech	19·2 μs	90°	−3·0 dB	24·1 μs	87°	−2·8 dB	31·6 μs	77°	−2·1 dB
Violin	25·0 μs	117°	−5·6 dB	27·7 μs	100°	−3·8 dB	35·5 μs	87°	−2·8 dB

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Fig. 2 — Effect of interchannel time difference on quality of compatible programme obtained by addition of identical left- and right-hand signals

(a) upper-frequency limit of programme 13 kc/s
(b) upper-frequency limit of programme 10 kc/s
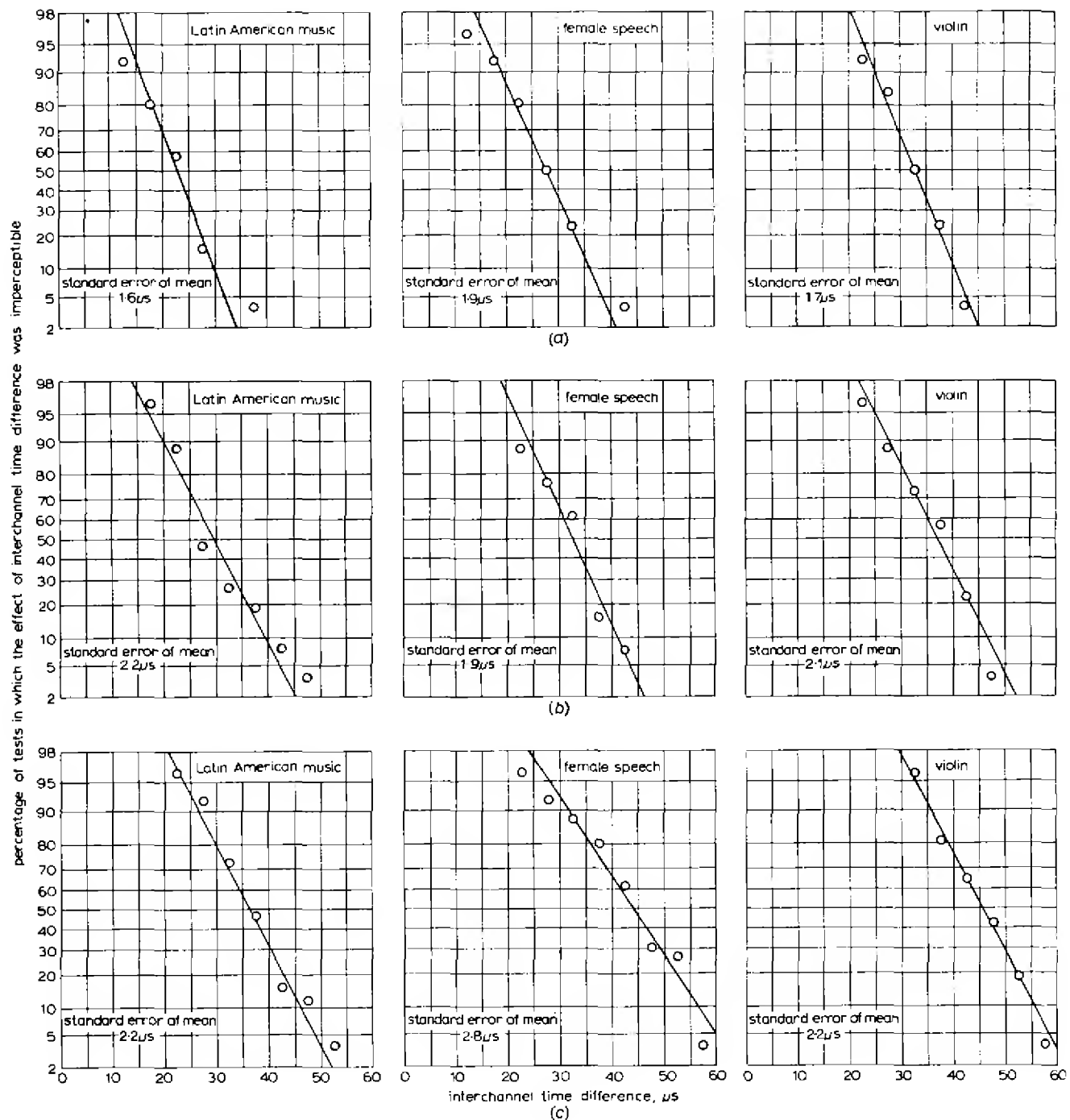(c) upper-frequency limit of programme 6·8 kc/s

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forty-six seconds; each passage was repeated again and again without a break until the observer had made his decision.

The tests were carried out under three conditions:

1. with the audio-frequency bandwidth of the programme material limited only by the characteristics of the loudspeaker, the frequency range of which extended to 13 kc/s;
2. with the upper frequency range of the material restricted to 10 kc/s by a low-pass filter;
3. with a similar restriction to 6·8 kc/s.

As in some previous experiments[6] involving impairment of quality by restricting the high-frequency response of the programme chain, it was found necessary to prevent the observer being influenced by changes in the spectrum of the background hiss, rather than in the spectrum of the programme; to this end, additional random noise, obtained from a gas discharge generator and sufficient to mask changes in the existing hiss, was injected into the circuit after the point at which the left- and right-hand signals were combined, but ahead of the low-pass filters.

3.1.2 Results

In Fig. 2 the interchannel time differences are shown as abscissae, while the percentage of tests in which the effect of the time difference was imperceptible are plotted to a Gaussian probability scale as ordinates. The standard error of the mean is indicated in each case.

Tables 1 and 2 show, for the three different bandwidths, the amount of interchannel time difference which was imperceptible in 50 per cent and 90 per cent of the tests respectively. For each bandwidth, the second column of the table shows the corresponding phase differences at the upper limit of the band. The third column shows the loss, at the upper limit of the band, to which a compatible signal derived by adding equal left- and right-hand signals would be subjected.

The interchannel time difference found to be imperceptible varies, as might be expected, between the individual items; however, comparison of the smallest delay shown in Table 2 with the largest shown in Table 1 for the same bandwidth shows a ratio of little more than two to one. It should be noted that restriction of the upper frequency range, while allowing greater time differences for the same impairment of monophonic quality, does not allow a greater phase angle, and hence a greater loss, to be tolerated at the upper end of the band.

In view of the suggestion, cited in Section 2, that the maximum allowable interchannel phase difference should be 90°, it is of interest to apply this criterion to the conditions of the present experiment. Since the phase difference here is proportional to frequency, the limiting case is that in which the figure of 90° is attained at the upper end of the band. The figures in Table 3, obtained by interpolation, show the percentage of tests in which the impairment of quality under these conditions would be imperceptible. It will be seen that with one exception—Latin-American music restricted to the 6·8 kc/s range—the subjective effect of the interchannel phase difference would be im-

perceptible in more than 70 per cent of the tests and may therefore be regarded as tolerable.

TABLE 3

Percentage of Tests in which the Effect of Interchannel Phase Difference Proportional to Frequency and Reaching 90° at the Upper End of the Frequency Band would be Imperceptible

Item	Upper Frequency Limit 13 kc/s	Upper Frequency Limit 10 kc/s	Upper Frequency Limit 6·8 kc/s
Latin-American music	74%	73%	48%
Female speech	90%	87%	78%
Violin	99%	95%	87%

3.2 Effect of Interchannel Phase Difference on Stereophonic Presentation

As already indicated in Section 2, the maximum interchannel time difference which can be allowed without detriment to the stereophonic presentation is of the order of 250 μs. For the purpose of the present investigation, a more accurate determination of this figure is unnecessary, since, as shown in Table 1, a limit of the order of 25 μs is already set by the requirements of the compatible programme.

4. Interchannel Phase Difference Increasing at Low Frequencies

4.1 Effect of Interchannel Phase Difference on Quality of Compatible Monophonic Signal

4.1.1 Experimental Details

The programme material consisted of recordings of musical excerpts played respectively on organ, double-bass (pizzicato), and bass drum. The low-frequency limit of the system cannot be defined as unambiguously as the high-frequency limit; in fact, the spectrum of the programme material was found to extend down to 40 c/s, at which frequency the free-field response of the loudspeaker was 3 dB below the mid-band level. The interchannel phase difference was provided by an all-pass network giving a phase shift varying inversely as the frequency and reaching 90° at 50 c/s. Fig. 3, curve (a), shows the variation of phase shift with frequency produced by this network and Fig. 1, curve (b), the resulting frequency characteristic obtained by taking the sum of the left- and right-hand signals.

The ability of the observers to detect the presence of the phase-shifting network in one channel was determined by a series of 'ABX' tests. In each such test, the chosen passage of programme was presented three times in close succession, the phase-shifting network being introduced at random in either one or two of the repetitions; the observers were then asked to say which of the first two conditions presented resembled the third.
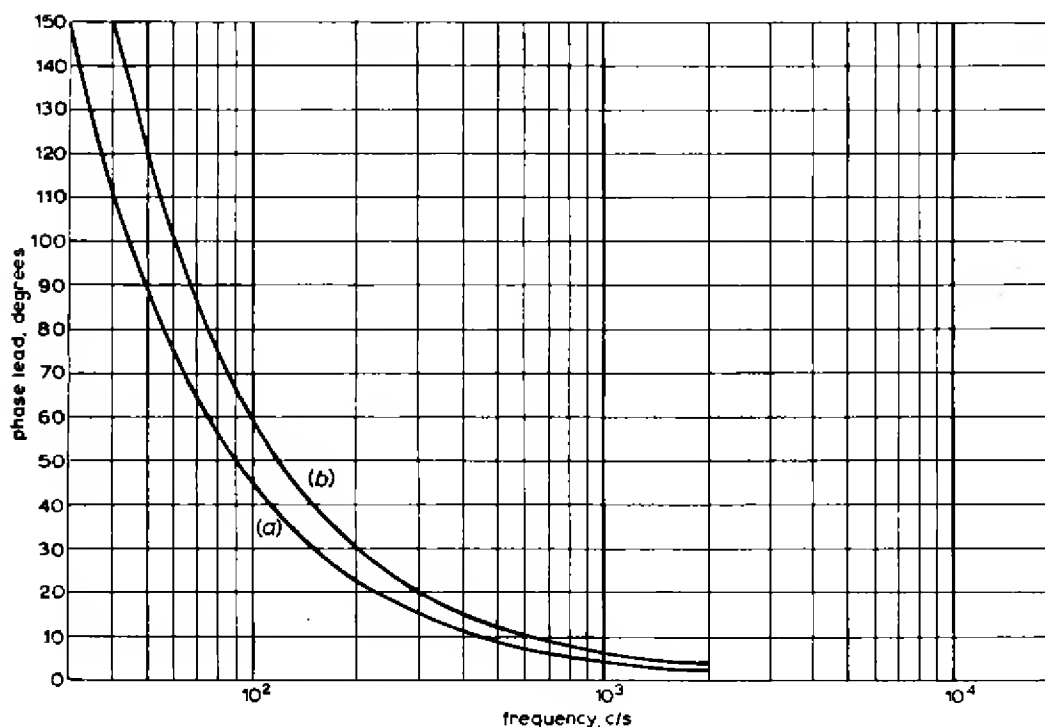
Fig. 3 — Phase-frequency characteristics of all-pass networks used for tests in low-frequency range

Interchannel phase difference inversely proportional to frequency
(a) reaching 90° at 50 c/s
(b) reaching 120° at 50 c/s

4.1.2 Results

For the test passage on the bass drum, 67 per cent of the observers correctly identified the test condition; for the organ and double-bass, however, the proportion of correct answers was respectively 54 and 53 per cent, i.e. not much greater than the 50 per cent figure which would have been obtained by chance. The effect, on the quality of the compatible programme, of an interchannel phase difference varying inversely with frequency and amounting to 90° at 50 c/s is therefore marginal.

4.2 Effect of Interchannel Phase Difference on Stereophonic Presentation

4.2.1 Experimental Details

The programme material was the same as that described in 4.1.1. In the first experiment, carried out in the listening room, each test passage was presented a number of times with the phase-shifting network referred to in Fig. 3, curve (a) alternately inserted and withdrawn; the observer was asked to state whether he detected any movement of the image, or of some component of it, and if so, in which direction. Although a high proportion of observers could detect the presence of the phase-shifting network (and the scores were found to increase slightly with practice) the movement of the image was too small to be estimated accurately. A further experiment was then

carried out with a second all-pass network having a phase shift varying, as shown in Fig. 3, curve (b), inversely with frequency and reaching 120° at 50 c/s; moreover, to increase the subjective effect, this network was switched alternately into the left- and right-hand channels, thus changing the interchannel phase difference at each frequency by twice the angle shown on the curve, e.g. by 240° for a 50 c/s component of the signal. The resulting effects on the stereophonic presentation were then large enough to allow of an accurate assessment, and the observers were accordingly asked to indicate, by means of a numbered scale, how far the edge of the image moved when the network was switched from one channel to the other. This experiment was repeated in the dead room.

In order to assess the contribution made by different parts of the programme spectrum to the total effect, both of the experiments described above were repeated with the low-frequency range of the programme restricted by a high-pass filter attenuating 3 dB at 200 c/s and having an ultimate rate of attenuation of 12 dB/octave.

4.2.2 Results

Table 4 shows the percentage of tests in which an observer in the listening-room, on the introduction of the phase-shifting network referred to in Fig. 3, curve (a), (90° at 50 c/s), reported a movement of the stereophonic

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image, or of some component of it, in the expected direction—i.e. away from that loudspeaker in which the signal was lagging in phase.

TABLE 4

Lower Frequency Limit 40 c/s			Lower Frequency Limit 200 c/s		
Organ	Drum	Double-bass	Organ	Drum	Double-bass
93%	99%	93%	86·5%	86·5%	87·5%

Although the displacements were too small to be accurately measured, the figures in the table are far above the 50 per cent which could have been obtained by chance. A remarkable feature of these results is the high score obtained with programme material restricted to the range above 200 c/s, at which frequency the interchannel phase shift introduced by the all-pass network was only 22·5°.

Table 5 shows the displacement of the edge of the image when the phase-shifting network referred to in Fig. 3, curve (b) (120° at 50 c/s), was switched from one channel to the other. The displacement is expressed in terms of the stage width, followed, in brackets, by the standard error (S.E.) of the mean.

It will be seen that in the passages for drum and for double-bass, removal of components having frequencies below 200 c/s produced a significant reduction in the observed displacements. For the organ music, however, this reduction was not large enough to be statistically significant; since the spectrum of the test passage was known to contain strong components at frequencies as low as 40 c/s, it must be assumed that the directional effect of components above 200 c/s was predominant.

The effect of acoustic environment is seen to be appreciable in most cases. The image displacements for the organ and double-bass—with or without restriction of the frequency range—are significantly smaller in the listening-room than in the dead room; for the drum the effect of room acoustics is not significant. It is also of interest that the results obtained in the dead room for each of the three instruments for either one of the frequency ranges do not differ significantly; on the other hand, those obtained in the listening room are significantly different for each instrument, at least for the particular excerpts chosen.

5. Conclusions on Part I

From the foregoing data it is possible to make a rough estimate of the interchannel phase tolerance which might be imposed on a compatible stereophonic system. The various limiting factors are presented in Fig. 4. Curve (a) in Fig. 4, reproduced from curve (a) in Fig. 3, shows a form of interchannel phase shift characteristic for which, as shown in Section 4, the effects on both monophonic quality and stereophonic presentation observed on programme are detectable but not serious.

The image displacement corresponding to curve (a) in Fig. 4 was too small to measure accurately, but may be estimated from Table 5, on the basis of rough proportionality, to be not greater than 0·04 of the stage width for the most critical type of programme material. Curve (b) in Fig. 4 shows the overall change in interchannel phase difference at frequencies above 200 c/s produced by switching the network having the phase characteristic shown in Fig. 3, curve (b) from one channel to the other; the corresponding image displacement, from Table 5, is seen to be not greater than 0·06 of the stage width. Thus, a tolerance curve intended to restrict unwanted image shifts to around 0·05 of the stage width could safely be placed somewhere between curves (a) and (b). Curve (c) in Fig. 4 shows the interchannel phase difference corresponding to an interchannel time difference of 200 μs, which, as already noted in Section 2, was originally proposed as a tolerance limit, and it seems logical to use this law as a rough guide from about 400 c/s upwards.

As far as the high-frequency components of the programme are concerned, it will be seen from Table 3 that for frequency bands extending respectively to 13 kc/s and 10 kc/s, interchannel phase differences proportional to frequency and reaching 90° at the upper end of the band are tolerable; these two conditions are represented by curves (d) and (e) respectively in Fig. 4. It should be emphasized that curves (a) to (e) give in each case the phase characteristics for a particular circuit condition which has been found acceptable on programme material covering a

TABLE 5

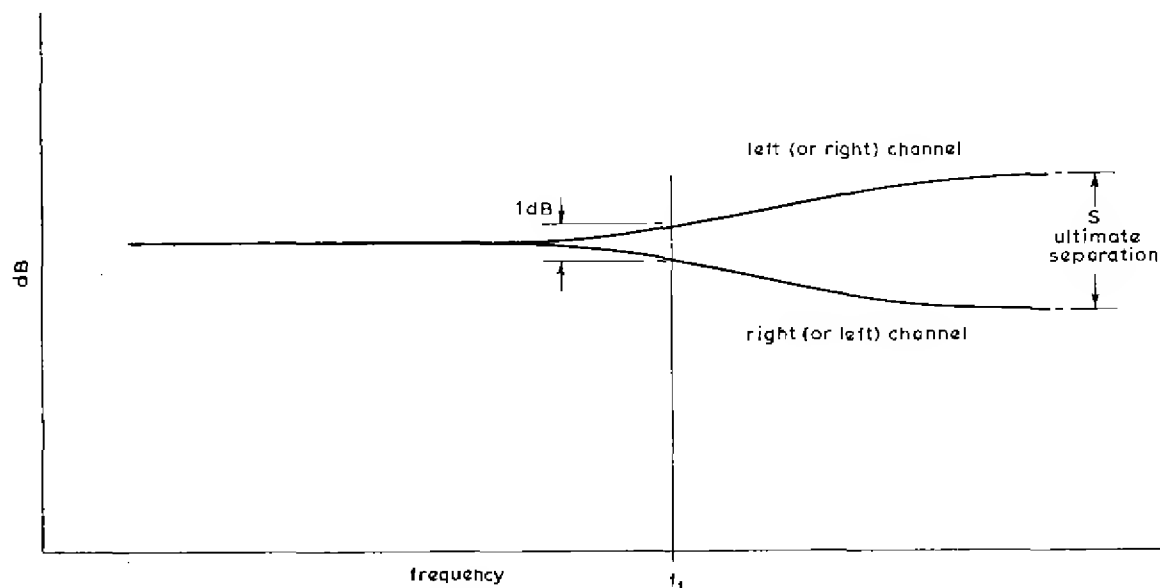|	Lower Frequency Limit 40 c/s			Lower Frequency Limit 200 c/s		
	Organ	Drum	Double-bass	Organ	Drum	Double-bass
Listening room	0·053 (S.E. 0·008)	0·108 (S.E. 0·009)	0·059 (S.E. 0·007)	0·047 (S.E. 0·006)	0·062 (S.E. 0·004)	0·032 (S.E. 0·005)
Dead room	0·077 (S.E. 0·011)	0·096 (S.E. 0·009)	0·082 (S.E. 0·012)	0·062 (S.E. 0·008)	0·C59 (S.E. 0·008)	0·048 (S.E. 0·007)

Fig. 7 — *Method of specifying degree of interchannel amplitude difference at high frequencies*

The limits shown in Fig. 6 embrace an infinite variety of amplitude/frequency characteristics, and for the present purpose it was necessary to make an arbitrary selection. Fig. 7 shows diagrammatically the form of characteristic, produced by resistance-capacitance networks, chosen for the experiments on interchannel amplitude differences increasing at high frequencies. In one series of experiments all the pairs of curves had the same ultimate separation S, the degree of impairment of the transmission being varied by altering the circuit capacitances, thus displacing the characteristics along the frequency scale without changing the form of the curves; for reference purposes, each condition was arbitrarily designated by the frequency f_1 at which the characteristics of the left- and right-hand channels diverged by 1 dB. In a second series, the degree of impairment was controlled by varying the circuit resistances, thus altering S; the value of the latter quantity was then used for reference. In both cases, the networks producing the desired amplitude/frequency characteristics were adjusted in steps by means of ganged rotary switches so arranged that an increase in response of one channel at any frequency was accompanied by a sub-
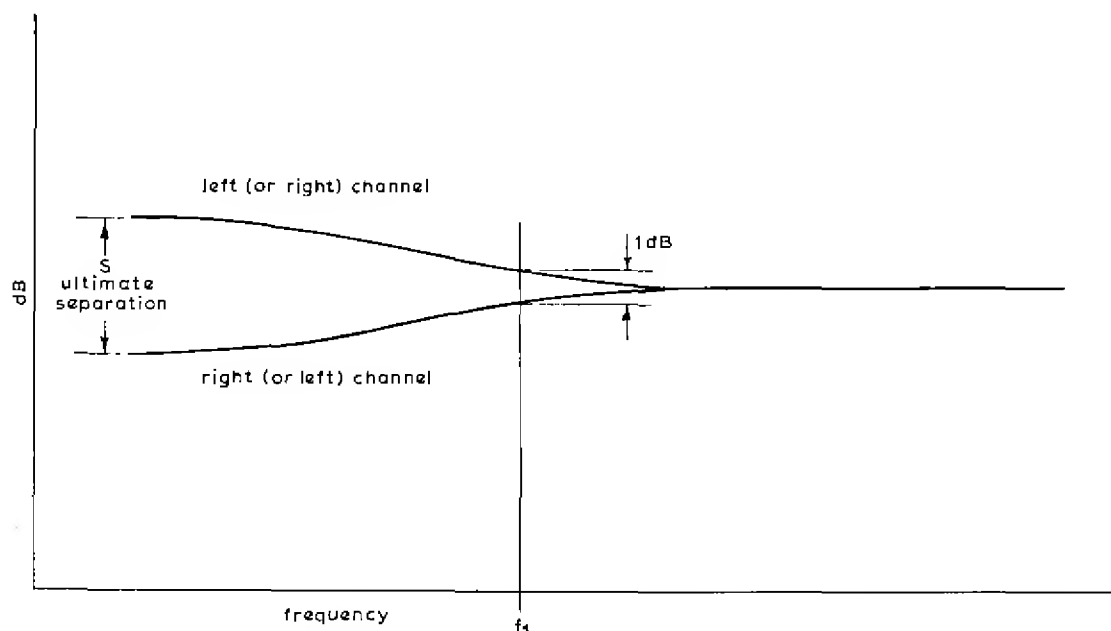

Fig. 8 — *Method of specifying degree of interchannel amplitude difference at low frequencies*

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stantially equal decrease (on a dB scale) in the response of the other.

In the case of interchannel amplitude differences increasing at low frequencies, the characteristics of the two channels took the form shown in Fig. 8, which is a mirror image of Fig. 7; from the results of a pilot experiment, however, it was considered unnecessary to carry out a second set of tests with S as the independent variable and the investigation was therefore confined to the effect of varying f_1.

No attempt was made to phase-compensate the circuits used to vary the amplitude/frequency characteristics of the two channels, any interchannel phase differences thereby introduced being accepted as a natural attribute of the system under investigation. In the event, these phase differences were found in the most extreme conditions to be less than 25° and it is clear from the results given in Part I that they could not have contributed appreciably to the subjective effect.

At the commencement of each group of tests, the rotary switch controlling the difference between the amplitude/frequency characteristics of the two channels was set at one end of its travel; in this condition identical signals were applied to the left- and right-hand channels, and the resulting image will be described for convenience as 'unimpaired'. The observer was asked to adjust a trimming attenuator controlling the relative levels of sound from the two loudspeakers until he judged the image to be central. He was then asked to operate the rotary switch controlling the interchannel difference in amplitude/frequency characteristic and to find (a) the first position for which a displacement of the image became perceptible, and (b) the setting for which the edge of the image coincided with some designated position on the numbered scale extending across the stage. Equal numbers of tests were carried out with the image displacement to the left and to the right; the various experimental conditions were presented in random order to avoid any recognizable sequence which might influence the observer's judgement.

Even when the left- and right-hand channels have identical amplitude/frequency characteristics, the resulting unimpaired image possesses a finite width which is a function, partly of any residual asymmetry in the sound-reproducing system, and partly of the listener's own resolving powers. In a supplementary experiment, carried out with the same programme material and the same bandwidth restrictions as in the main experiment, each observer was asked to estimate the width of a central unimpaired image.

7. Interchannel Amplitude Differences Increasing at High Frequencies

7.1 Experimental Details

The programme material used for these tests was a recorded excerpt of Latin-American music, repeated as many times as was necessary for the observer to reach a decision.

The susceptibility of a stereophonic presentation to changes in the relationship between the left- and right-hand signals at high frequencies is known from earlier experiments[2] to be little affected by a reduction in the normal amount of reverberation. It was therefore considered unnecessary to repeat any of the tests in the dead room.

As in previous experiments in this series, an attempt was made to assess the part played by components in the upper part of the audio-frequency range. To this end, some of the tests were carried out with the bandwidth of the system limited to 10 kc/s or 6·8 kc/s by low-pass filters; in the absence of the filters, the upper frequency limit was set at 13 kc/s by the characteristics of the loudspeakers employed.

The amplitude/frequency characteristics of the left- and right-hand channels obtained by varying f_1 are indicated in Fig. 9; the observer's control switch operated in eleven steps, but for clarity the characteristics for alternate steps

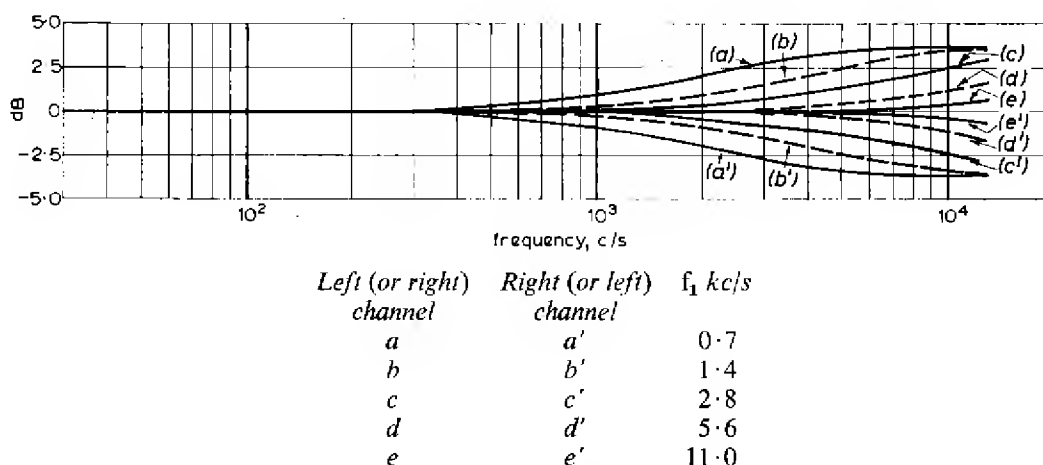| Left (or right) channel	Right (or left) channel	f_1 kc/s
a	a'	0·7
b	b'	1·4
c	c'	2·8
d	d'	5·6
e	e'	11·0

Fig. 9 — Amplitude/frequency response curves of networks used to introduce interchannel amplitude differences at high frequencies. (Alternate steps shown.) f_1 variable

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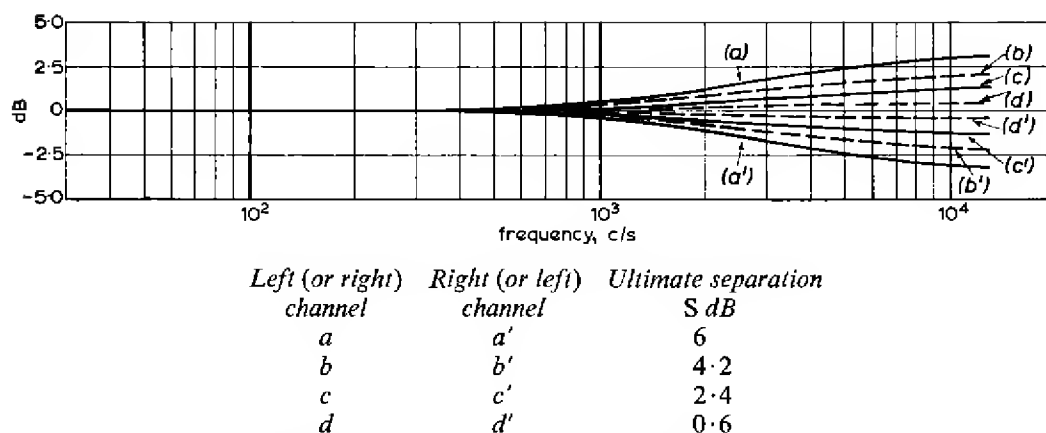| Left (or right) channel	Right (or left) channel	Ultimate separation S dB
a	a'	6
b	b'	4·2
c	c'	2·4
d	d'	0·6

Fig. 10 — Amplitude/frequency response curves of networks used to introduce interchannel amplitude differences at high frequencies.
(Every third step shown.)   S variable

only are given in the figure. Fig. 10 shows corresponding pairs of characteristics obtained by varying S; in this case the characteristics are given for every third step. The pairs of characteristics in Fig. 9 were obtained by altering the reactances in the circuit, the ultimate separation S remaining constant at 7·5 dB; in Fig. 10 the reactances were kept constant at such values that with S = 6 dB, f_1 = 1 k/c.

7.2 Results

Figs 11(a), 11(b), and 11(c) show the results obtained with the upper frequency range restricted to 13 kc/s, 10 kc/s, and 6·8 kc/s respectively, when the interchannel amplitude difference was varied, as shown in Fig. 9, by altering f_1; values of f_1 are plotted as abscissae to a logarithmic frequency scale so arranged that the degree of impairment of the system increases from left to right; the ordinates are plotted to a Gaussian probability scale. Curve (i) in each case shows the percentage of observations in which there was no perceptible image displace-

ment; curve (ii) shows the percentage of observations in which the edge of the image was less than 0·1 of the stage width from the centre; and curve (iii), the corresponding data for images reaching less than 0·2 of the stage width from the centre.

In most of the experiments the points fall nearly on a straight line indicating a Gaussian distribution. However, in these and similar figures given later, the lines representing different degrees of image impairment are in some cases not parallel and would therefore intersect if extrapolated; evidently the Gaussian distribution holds only over a limited range. The difference in slope between the lines, which, whenever it is statistically significant, indicates a decrease in standard deviation with decreasing image impairment, may be due partly to the finite width of the image.

Table 6 is derived from Figs 11(a), 11(b), and 11(c). It shows the values of f_1 for which, in 50 per cent of the observations, the subjective impairment of the image caused

TABLE 6

Tests in Listening-room

| Subjective impairment of nominally central image in 50 per cent of observations	Frequency range restricted to 13 kc/s		Frequency range restricted to 10 kc/s		Frequency range restricted to 6·8 kc/s	
	f_1 kc/s	S.E. (octave)	f_1 kc/s	S.E. (octave)	f_1 kc/s	S.E. (octave)
Imperceptible	10·5	0·15	9·3	0·15	5·4	0·1
Edge of image off-centre by less than 0·1 stage width	5·1	0·3	4·3	0·25	2·9	0·2
Edge of image off-centre by less than 0·2 stage width	1·7	0·25	1·6	0·25	1·2	0·25

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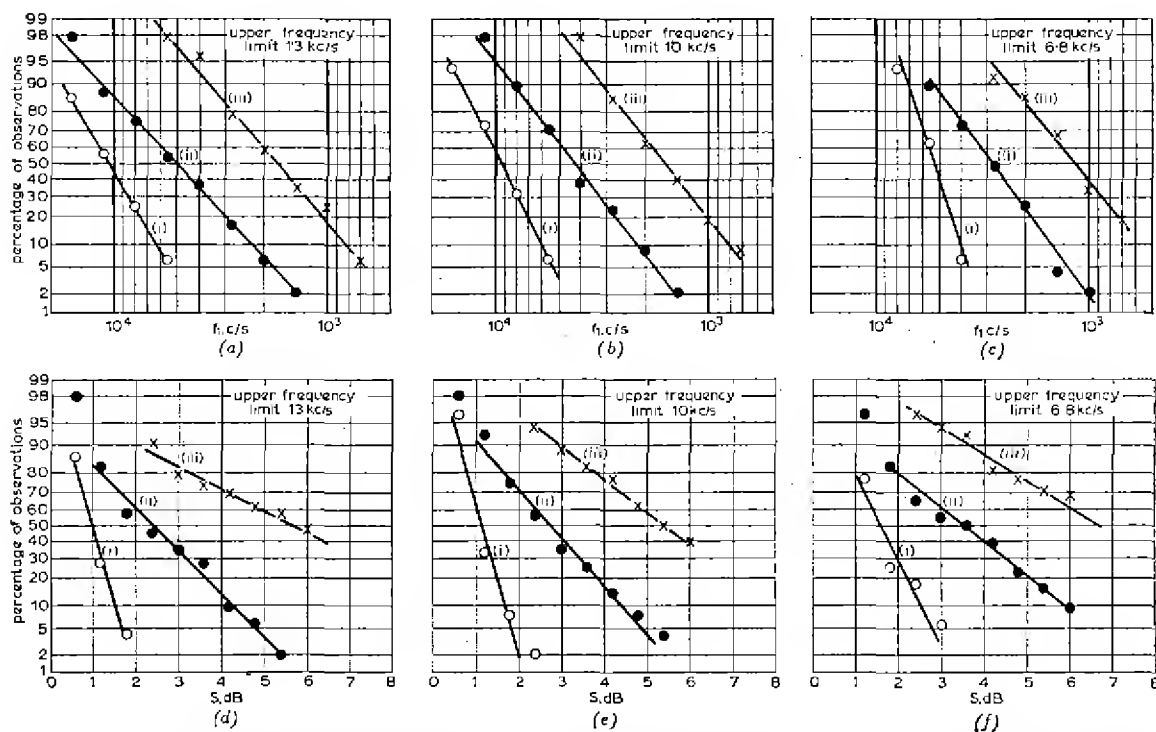
Fig. 11 — *Subjective effect of difference between amplitude/frequency characteristics of left and right channels at high frequencies. Divergence of channels expressed in* (a), (b), *and* (c) *in terms of* f_1, *in* (d), (e), *and* (f) *in terms of* S

Numbering of curves:
    (i) Percentage of observations in which there was no perceptible image displacement.
    (ii) Percentage of observations in which the edge of the image was less than 0·1 stage width from the centre.
    (iii) Percentage of observations in which the edge of the image was less than 0·2 stage width from the centre.

by the interchannel amplitude difference can be classified as 'imperceptible', 'edge of image off-centre by less than 0·1 of stage width', and 'edge of image off-centre by less than 0·2 of stage width' respectively. The standard error of the mean (S.E.) is given in each case to the nearest 0·05 octave.

Figs 11(d), 11(e), and 11(f) show the results obtained with the upper frequency range restricted to 13 kc/s, 10 kc/s, and 6·8 kc/s respectively when the interchannel amplitude difference was varied, as shown in Fig. 10, by altering S. Apart from the change in the independent variable, the remarks already made with regard to Figs 11(a), 11(b), and 11(c) apply here also. However, since there can be no impairment of the image when the interchannel amplitude difference is zero, there is an inevitable departure from Gaussian distribution as the curves approach S = 0.

Table 7, derived from Figs 11(d), 11(e), and 11(f), shows the values of S, in dB, for which, in 50 per cent of the observations, the effect of the interchannel amplitude difference can be classified as 'imperceptible', 'edge of image off-centre by less than 0·1 of stage width', and 'edge of image off-centre by less than 0·2 of stage width' respectively. The standard error of the mean is given in each case to the nearest 0·1 dB.

As already stated in Section 6, a supplementary experiment was carried out to find the width of a central image produced with identical left- and right-hand channels. For the Latin-American music referred to above, the mean image width was found in this experiment to be 0·1 of the stage width (S.E. 0·01) with no significant difference between the results for the three bandwidths. This means that the unimpaired image was regarded by the observers as extending, on average, one half of this, i.e. 0·05 of the stage width on either side of the centre. It follows that if the image is spread towards either side as a result of some system impairment and extends, for example, to 0·2 on the numbered scale, the edge of the image must have been displaced by only 0·15.

So far the impairment in the stereophonic transmission system has for convenience been expressed in terms of the arbitrary quantities f_1 and S. It is now necessary to reverse the process and to consider what differences between the amplitude/frequency characteristics of the left- and right-hand channels are associated with a particular subjective grading. The result is shown in Figs 12, 13, and 14, which are derived from Fig. 11 by interpolation. Fig. 12 shows the amplitude/frequency characteristics of the two channels for which the displacement of the image would in 50 per cent of the tests be imperceptible. The data are given for

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TABLE 7

Tests in Listening-room

Subjective impairment of nominally central image in 50 per cent of observations	Frequency range restricted to 13 kc/s		Frequency range restricted to 10 kc/s		Frequency range restricted to 6·8 kc/s	
	S dB	S.E. dB	S dB	S.E. dB	S dB	S.E. dB
Imperceptible	1·0	0·1	1·2	0·1	1·6	0·2
Edge of image off-centre by less than 0·1 stage width	2·4	0·4	2·7	0·4	3·5	0·6
Edge of image off-centre by less than 0·2 stage width	5·6	0·8	5·4	0·6	6·7	0·7

the three bandwidths; the full line and dashed curves relate respectively to the results obtained by varying f_1 and S. Fig. 13 shows the amplitude/frequency characteristics of the two channels for which, in 50 per cent of the observations, the edge of the image would be off-centre by less than 0·1 of the stage width, and Fig. 14 the corresponding data for 0·2 of the stage width.

It will be seen that in Figs 12, 13, and 14, each curve relating to variation in S intersects the corresponding curve relating to variation in f_1; it seems likely that the subjective assessment in each case was influenced largely by components having frequencies in the region of intersection.

It will also be noticed that for each subjective grading, the degree of divergence between the amplitude/frequency characteristics of the left- and right-hand channels at the upper end of the band is nearly independent of the bandwidth.
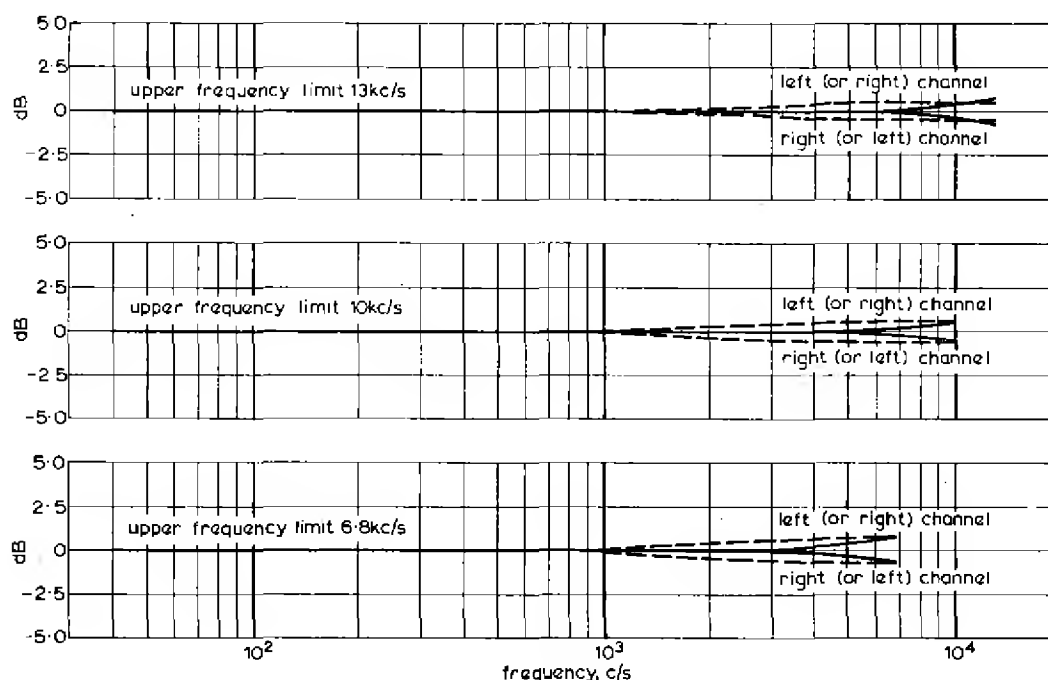

Fig. 12 — *Amplitude/frequency characteristics of left and right channels at high frequencies for which there was no perceptible image displacement in 50 per cent of observations*

————f_1 variable   - - - - -S variable

Fig. 13 — *Amplitude/frequency characteristics of left and right channels at high frequencies for which the edge of the image was less than* 0·1 *stage width from centre in 50 per cent of observations*
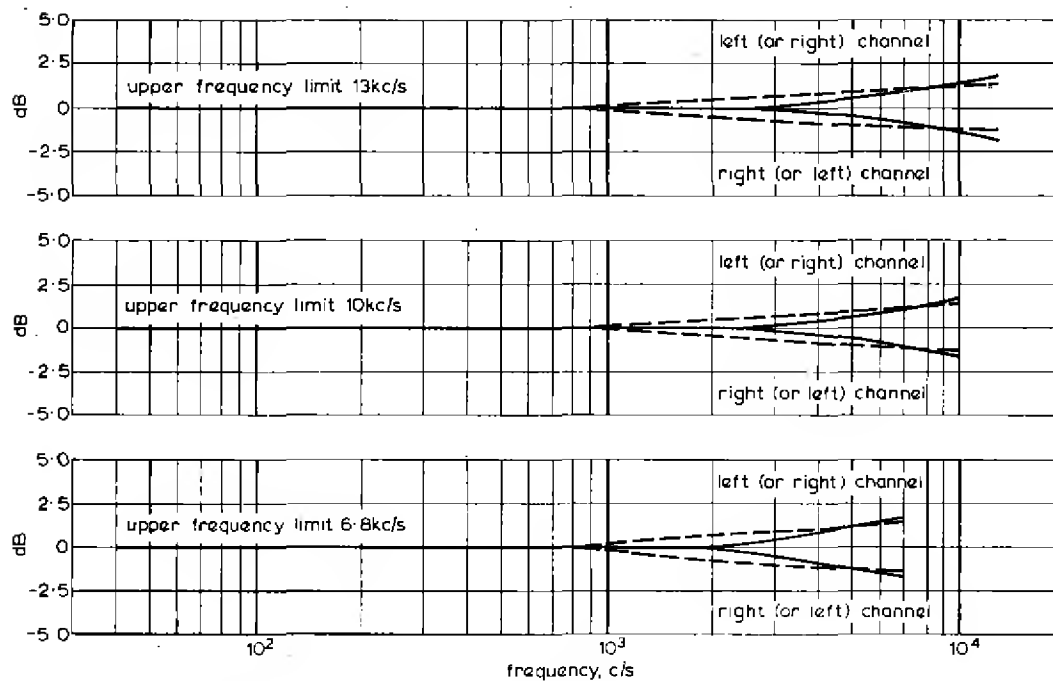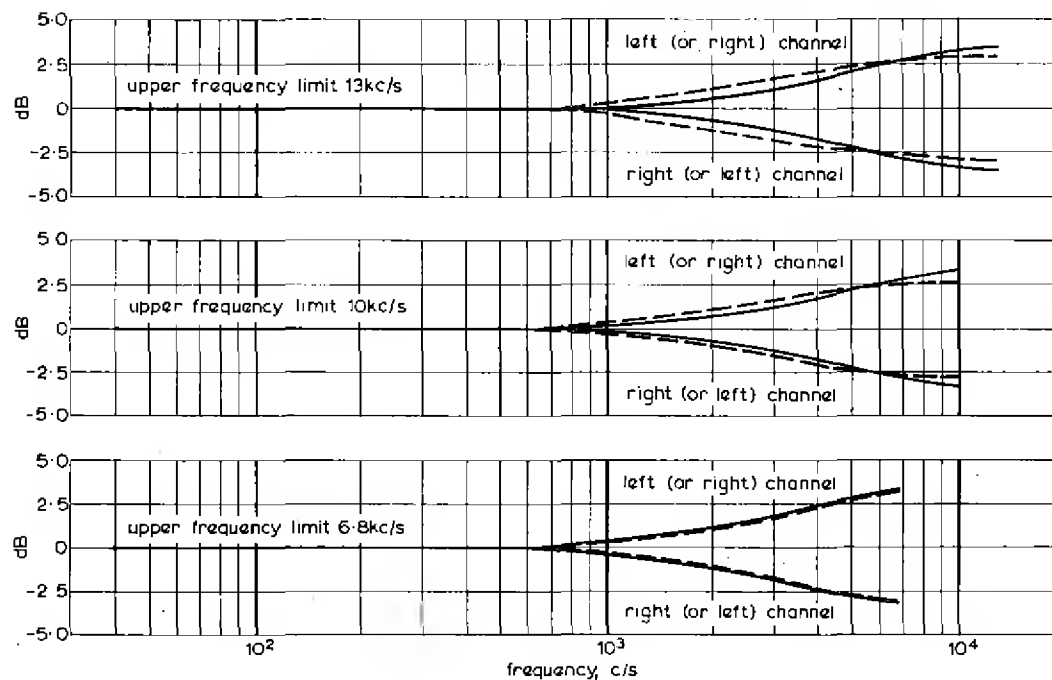
————f₁ variable   - - - - -S variable

Fig. 14 — *Amplitude/frequency characteristics of left and right channels at high frequencies for which the edge of the image was less than* 0·2 *stage width from centre in 50 per cent of observations*

————f₁ variable   - - - - -S variable

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8. Interchannel Amplitude Differences Increasing at Low Frequencies

8.1 Experimental Details

The programme material consisted of excerpts from recorded solos on organ, bass drum, and double bass played pizzicato; the test passages were repeated until the observer had come to a decision.

From previous experience[4] it was thought possible that the results of this part of the experiment might be significantly affected by a reduction in the amount of reverberation in the listening area. Tests were therefore carried out both in the listening-room and in the dead room.

As long as the interchannel amplitude differences below 1 k/c did not exceed the limits given in Fig. 6, the maximum impairment of the stereophonic presentation was not large enough to justify closer analysis by the introduction of filters to restrict the frequency band; tests were there-fore made only with the full frequency range, limited at its lower end to approximately 40 c/s by the nature of the programme material and the characteristics of the loud-speakers. For the same reason it was thought sufficient to control the difference between the amplitude/frequency characteristics of the left- and right-hand channels by varying the frequency f_1 at which the curves diverge by 1 dB, the value of S being held constant at 6 dB. Fig. 15 shows the form of characteristic obtained by this means; as in the corresponding curves in Fig. 9, eleven different pairs of characteristics could be produced, but for clarity, only alternate steps are shown.

8.2 Results

Figs 16(a), 16(b), and 16(c) show the results of the tests in the listening-room for organ, drum, and double-bass respectively. Curve (i) in each case shows the percentage

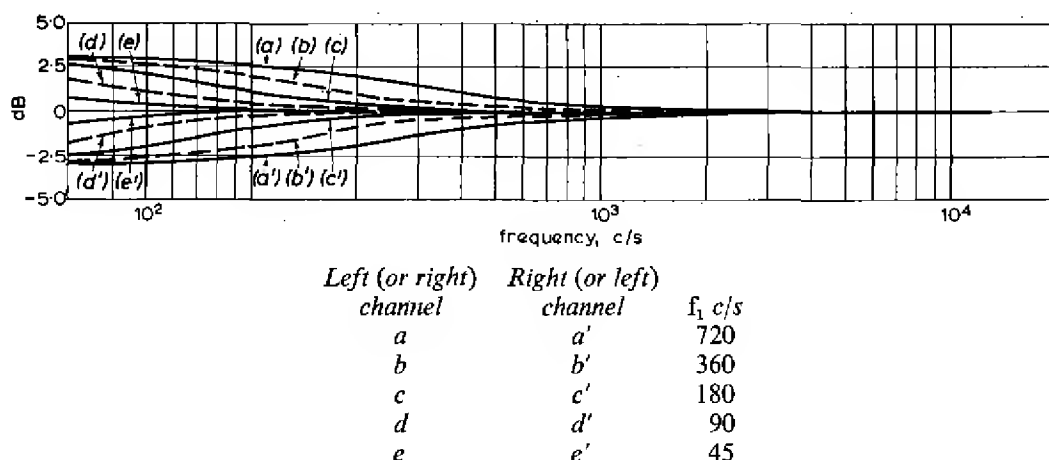| Left (or right) channel	Right (or left) channel	f_1 c/s
a	a'	720
b	b'	360
c	c'	180
d	d'	90
e	e'	45

Fig. 15 — Amplitude/frequency response curves of networks used to introduce interchannel amplitude differences at low frequencies. (Alternate steps shown.) f_1 variable
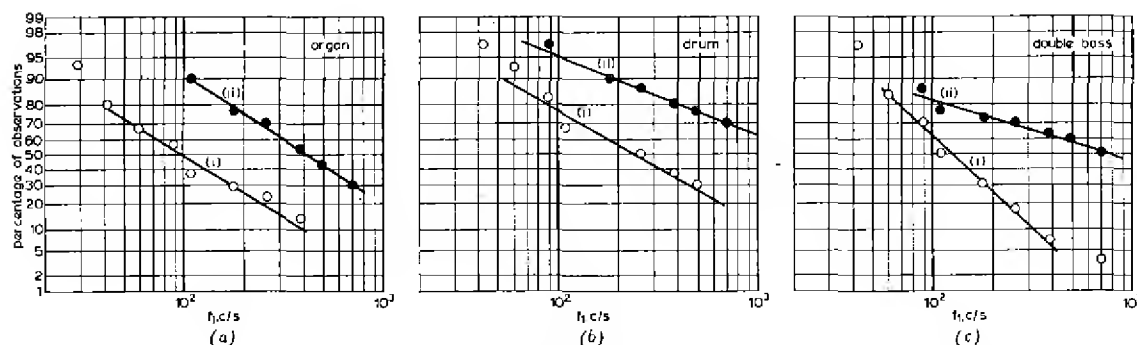

(a)　　　　　(b)　　　　　(c)

Fig. 16 — Subjective effect of difference between amplitude/frequency characteristics of left and right channels at low frequencies. Divergence of channels expressed in terms of f_1

Numbering of curves:
(i) Percentage of observations in which there was no perceptible image displacement.
(ii) Percentage of observations in which the edge of the image was less than 0·1 stage width from centre.

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of observations in which there was no perceptible image displacement, and curve (ii) the percentage of observations in which the edge of the image was less than $0 \cdot 1$ stage width from the centre. Even with the maximum interchannel difference between amplitude/frequency characteristics indicated in Fig. 15, the image rarely extended as far as $0 \cdot 2$ on the scale and the data was therefore insufficient to allow a reliable curve to be drawn for this condition. As in the corresponding curves in Fig. 11, the abscissae are plotted to a Gaussian probability scale, and the curves of best fit approximate to straight lines. It will be noted that whereas Fig. 11 covers three different bandwidths, Fig. 16 relates to three different musical instruments.

ment on the width of a central image depends to some extent on the part of the spectrum involved.

As explained in Section 7.2, the distance by which the edge of the image was displaced in reaching a particular position on the numbered scale can be estimated by subtracting from the scale reading one half the width of the unimpaired central image.

Figs 17 and 18, derived from Fig. 16 by interpolation, show the amplitude/frequency characteristics of the left- and right-hand channels for which, in 50 per cent or more of the observations, the subjective impairment would be classified respectively as 'imperceptible' and 'edge of image off-centre by less than $0 \cdot 1$ of stage width'. It will be seen that for the same degree of image impairment, a

TABLE 8

Tests in Listening-room

Subjective impairment of nominally central image in 50 per cent of observations	Organ		Drum		Double-bass	
	f_1 c/s	S.E. (octave)	f_1 c/s	S.E. (octave)	f_1 c/s	S.E. (octave)
Imperceptible	96	$0 \cdot 4$	240	$0 \cdot 45$	124	$0 \cdot 3$
Edge of image off-centre by less than $0 \cdot 1$ stage width	406	$0 \cdot 4$	1,700	$0 \cdot 65$	760	$0 \cdot 85$

Table 8, derived from Figs 16(a), 16(b), and 16(c), shows the values of f_1 for which, in 50 per cent or more of the observations, the effect of the interchannel amplitude difference can be classified as 'imperceptible', and 'edge of image off-centre by less than $0 \cdot 1$ of stage width' respectively. The standard error of the mean is given in each case to the nearest $0 \cdot 05$ octave.

In the dead room the values of f_1 obtained were nearly the same as those shown in Table 8 and are not therefore reproduced here. Such small differences as existed between the two sets of figures, though barely significant statistically, suggested that the effects of interchannel amplitude differences were, if anything, less noticeable in the dead room than in the listening room.

The supplementary experiment carried out to determine the width of an unimpaired central image yielded results which were in some cases significantly larger than those given in Section 7.2. The average image width in the listening-room was $0 \cdot 14$, $0 \cdot 13$, and $0 \cdot 09$ of the stage width for the organ, drum, and double-bass respectively, the standard error being about $0 \cdot 013$ of the stage width in each case. In the dead room the image width was slightly less for the drum and double-bass, though for the organ, which has a greater middle frequency content, no significant difference was observed. In some later experiments with male speech (which contains no very low-frequency components) the image was found to be narrower in the listening-room than in the dead room; it appears, therefore, that at low frequencies the effect of the acoustic environ-

much greater divergence between the channel characteristics could be permitted at low than at high frequencies.

9. Conclusions on Part II

From the foregoing information it is now possible to consider the tolerances which might be imposed in practice on the matching of the amplitude/frequency characteristics of the left- and right-hand channels of a stereophonic system. To this end, it is convenient to replot the curves of Figs 12, 13, 14, 17, and 18 to show, instead of the actual amplitude/frequency characteristics of the two channels, the difference between the two; the resulting data is presented in Figs 19, 20, and 21 for the high-frequency range and in Figs 22 and 23 for the low-frequency range.

In drawing conclusions from this data, the following points should be specially noted:

(a) The experiments were confined to the case in which the amplitude/frequency characteristics of the left- and right-hand channels depart from uniformity by equal and opposite amounts. In applying the results to the more general case, it is tacitly assumed that dispersion of the stereophonic image is unaffected by changes in amplitude/frequency characteristic applying to both channels equally.

(b) The curves in Figs 19 to 23, like the curves from which they are derived, represent a circuit condition for which the effects described earlier were observed
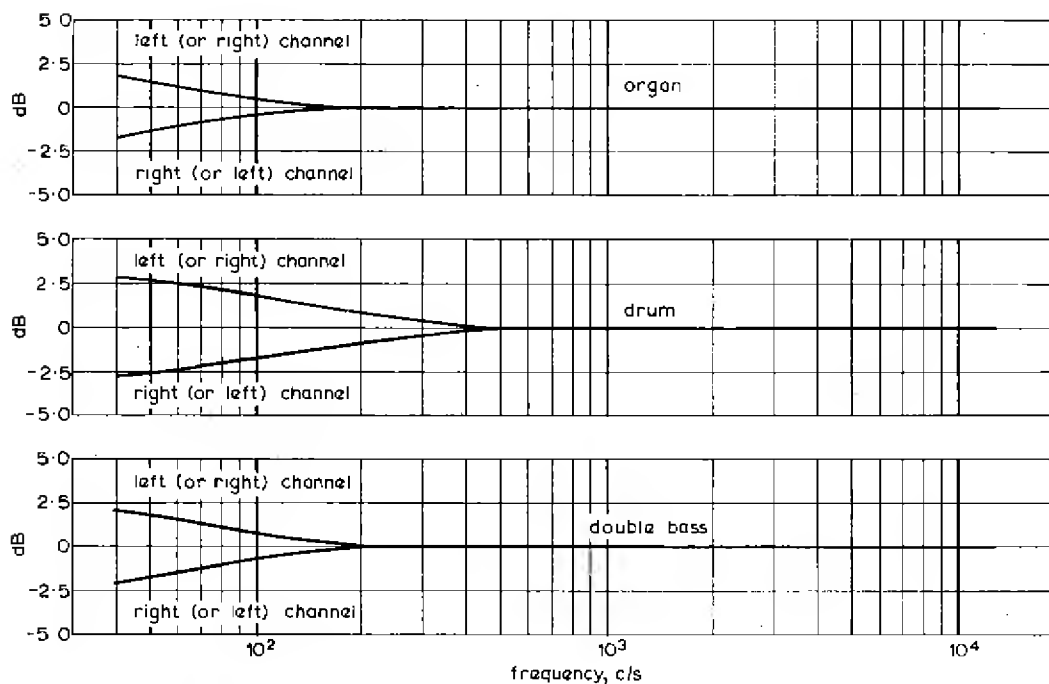
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Fig. 17 — Amplitude/frequency characteristics of left and right channels at low frequencies for which there was no perceptible image displacement in 50 per cent of observations
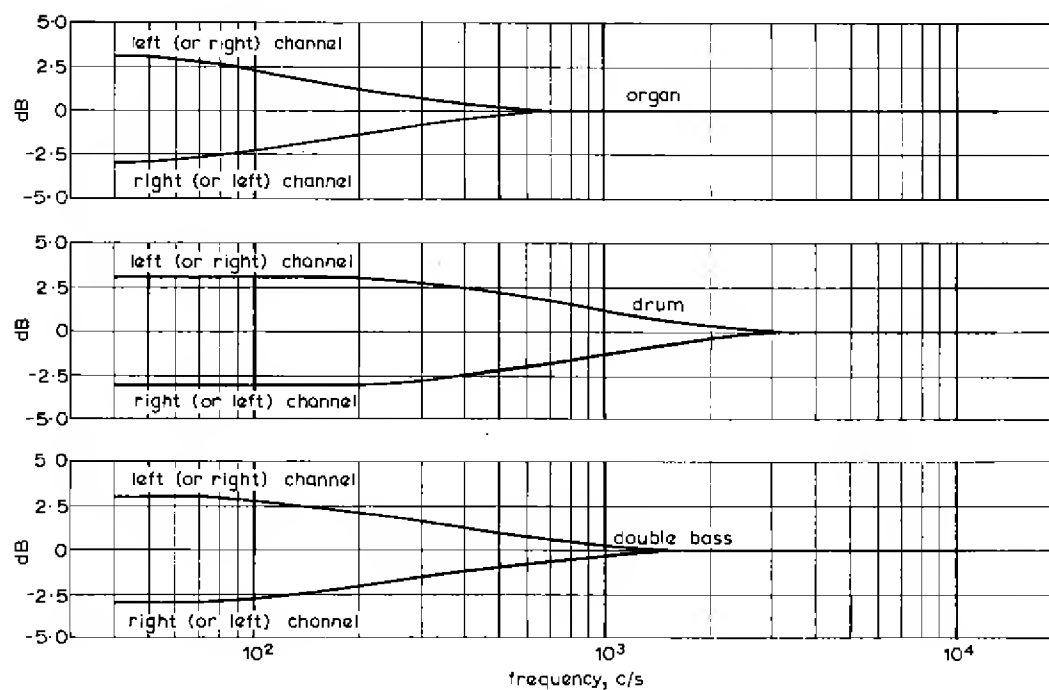
———f_1 variable

Fig. 18 — Amplitude/frequency characteristics of left and right channels at low frequencies for which the edge of the image was less than $0 \cdot 1$ stage width from centre in 50 per cent of observations
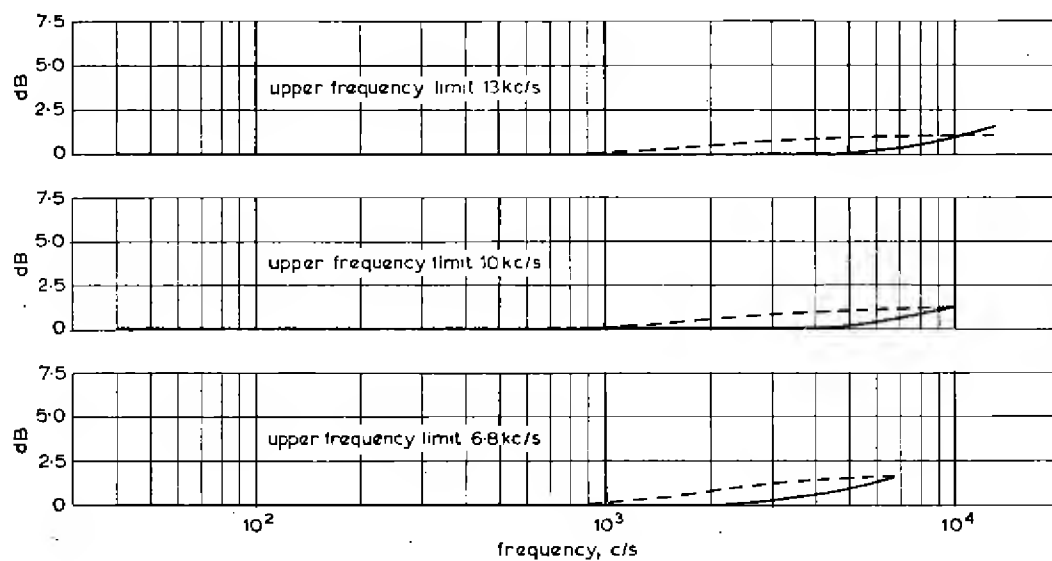
———f_1 variable

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Fig. 19 — Difference between amplitude/frequency characteristics of left and right channels for which there was no perceptible image displacement in 50 per cent of observations Frequency characteristics of left and right channels diverging at high frequencies
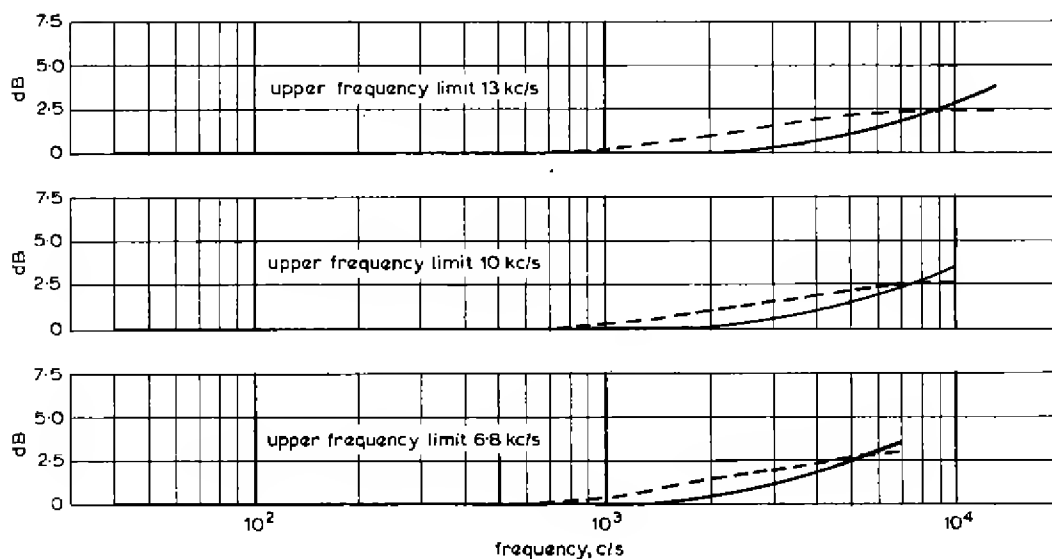
————f_1 variable   - - - - -S variable

Fig. 20 — Difference between amplitude/frequency characteristics of left and right channels for which the edge of the image was less than 0·1 stage width from centre in 50 per cent of observations Frequency characteristics of left and right channels diverging at high frequencies
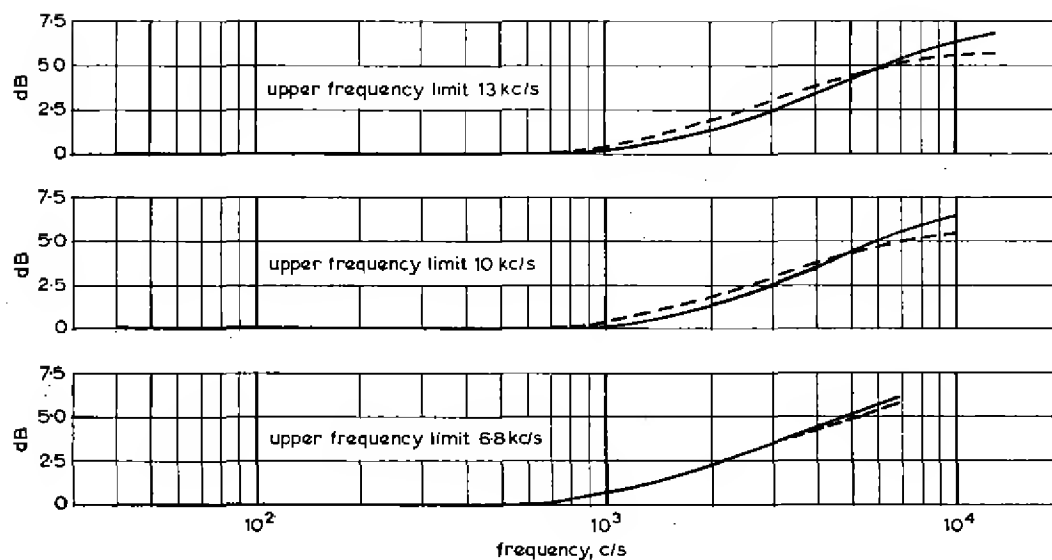
————f_1 variable   - - - - -S variable

23

Fig. 21 — Difference between amplitude/frequency characteristics of left and right channels for which the edge of the image was less than 0·2 stage width from centre in 50 per cent of observations
Frequency characteristics of left and right channels diverging at high frequencies

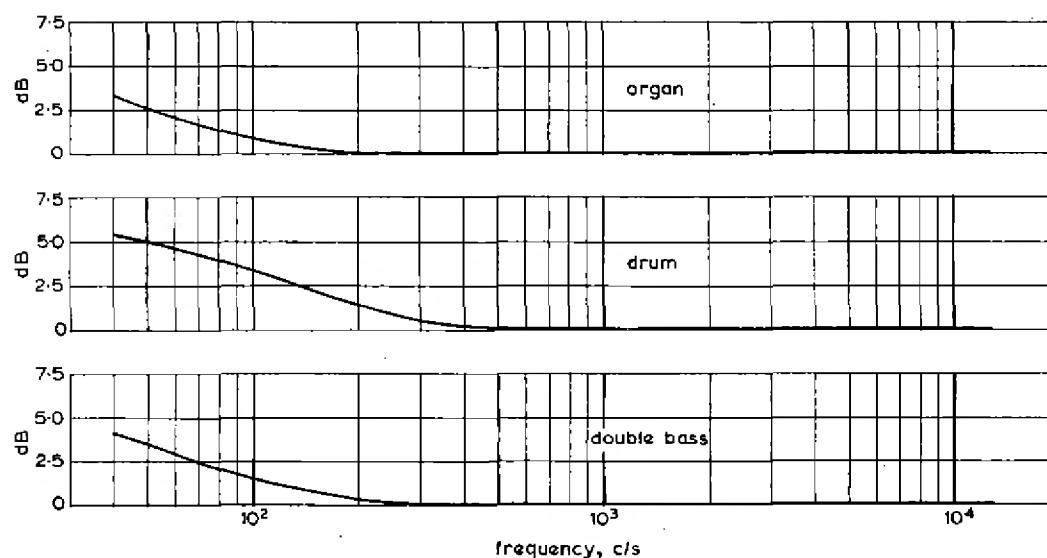———f₁ variable   - - - - -S variable

Fig. 22 — Difference between amplitude/frequency characteristics of left and right channels for which there was no perceptible image displacement in 50 per cent of observations
Frequency characteristics of left and right channels diverging at low frequencies
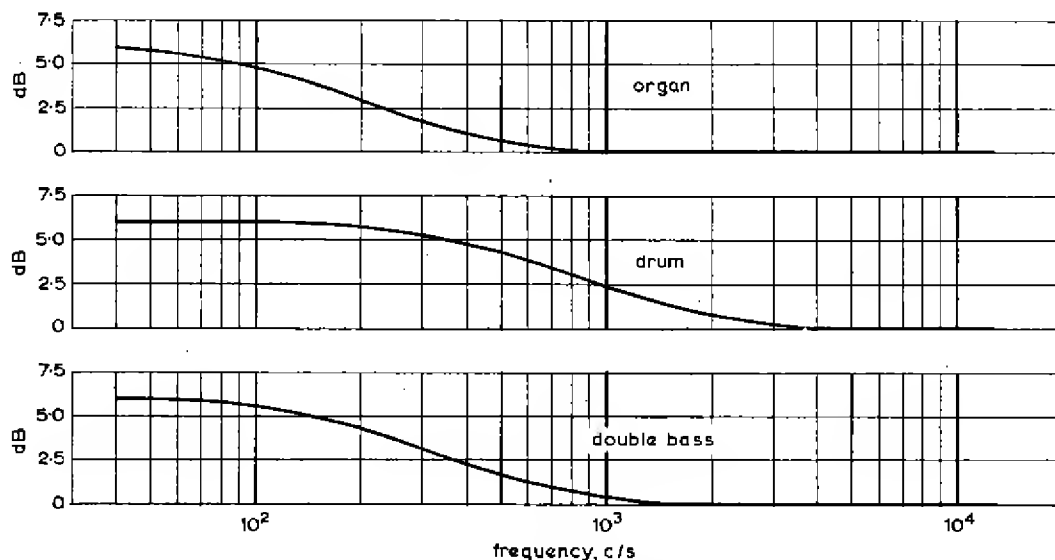
———f₁ variable

24

Fig. 23 — Difference between amplitude/frequency characteristics of left and right channels for which the edge of the image was less than 0·1 stage width from centre in 50 per cent of observations
Frequency characteristics of left and right channels diverging at low frequencies
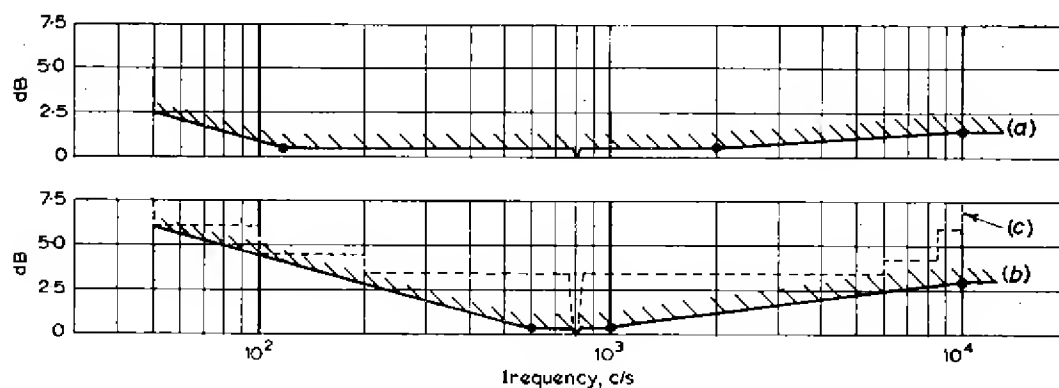
——— f_1 variable

Fig. 24

(a), (b) Suggested tolerances for difference between frequency characteristics of left and right channels taking gain or loss of 800 c/s as zero.
(a) Limit of perceptibility. (b) Acceptable limit if necessary
(c) Overall limit of variation in frequency characteristic permitted by CCITT tolerances of normal Type A programme circuits.

on programme material covering a range of frequencies; they do not represent the effect of differences in the gain or loss of the left- and right-hand channels at any one frequency considered separately.

(c) Interchannel amplitude differences may be of opposite sign at the two ends of the audio-frequency band. A nominally central image having components at both extremes of the band could then be dispersed both to left and to right, the overall width being determined by the sum of the two effects.

It seems reasonable to consider two degrees of tolerance, the first based on the most critical case and the second representing a practical compromise when the more stringent requirements cannot be met. The former limit could be derived from the data for imperceptible impairment in 50 per cent of cases; the latter could appropriately be arrived at by assuming the edge of a nominally central image to be, in 50 per cent of cases, off-centre by less than 0·1 of a stage width. In Fig. 24 an attempt has been made to draw up a set of tolerances on these lines. It is assumed that the gain or loss of the left- and right-hand channels is

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made equal at 800 c/s; an arbitrary tolerance of 0·5 dB has been allowed in the mid-band region. Curve (a) represents the limit of perceptibility, below which it is unnecessary to go, curve (b) the higher limit, representing a detectable but small degree of impairment. The dotted line (c) shows for comparison the possible differences in amplitude/frequency characteristic between two lines conforming to the limits specified by the Comité Consultatif International Télégraphique et Téléphonique (CCITT) in 1960 for normal Type A programme circuits.

10. Acknowledgements

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